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Comparison of salt solution and air drying methods for moisture fixation in highly porous building materials

Yovko Ivanov Antonov^{a*}, Rasmus Lund Jensen^a, Per Møldrup^a, Michal Pomianowski^a

^a*Department of Civil Engineering, Thomas Manns Vej 23, Aalborg Ø 9220, Denmark*

Abstract

In recent years, research has identified some bio-based, porous building materials as good or excellent regulators of moisture in buildings. The ability of a material to absorb, release and store moisture is described by vapour sorption isotherms. It is necessary input to simulations of indoor environmental parameters in regards to human comfort, and nowadays it can be determined by a number of laboratory experiments, each of which characterized by specific specimen size, equilibration time and methodology.

The purpose of this study is to experimentally derive isotherms for three bio-based, porous building materials by a standardized testing method, using saturated salt solutions. Furthermore, results from the standard method are compared to values of moisture content for the same materials, obtained by air-drying at different relative humidity. This is done with the aim to compare the findings from the two methods with respect to time and repeatability of the results.

Derived isotherms are further used as direct input in the building simulation software BSim, which is capable of predicting indoor environment parameters by solving coupled, transient heat and moisture transport equations using finite volume method discretization. Indoor air relative humidity and moisture content distribution in the construction are compared for the experimented materials and conventional building materials. Results show better agreement between isotherms obtained by standard method and air-drying for low density materials. Simulation results suggest that bio-based, highly porous building materials are comparable to conventional building materials in respect to air relative humidity variations, compared to conventional building materials.

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Keywords: HAM Simulations, Hempcrete, Vapor sorption isotherms

1. Introduction

Every building material is capable of exchanging certain amount of moisture with its surroundings. This ability of building materials plays an important role in the indoor environment in regards to human comfort and wellbeing. It is characterized by vapor sorption isotherms, which is a curve describing moisture fixation in building materials as a function of relative humidity (RH). A single value describing the moisture buffering potential can also be used to characterize building materials in regards to moisture storage. This is the moisture buffer value, defined by the NORDTEST Project [1]. Rode and Grau [2] discovered that taking moisture buffering of building materials into account can prompt energy savings when the ventilation is controlled by RH.

* Corresponding author. Tel.: +4-522-823-744.
E-mail address: yia@civil.aau.dk

Hemp-lime building materials are highly porous building materials that have been found to have either good or excellent moisture buffer values [3,4]. Those materials also seem to be good alternatives to conventional building materials due to their carbon negative footprint [5], and moderate thermal properties [6,7].

The aim of this paper is to determine the vapor sorption isotherms for three distinct hemp-lime building materials using saturated salt solutions. Moisture content found by salt solutions is compared to moisture content of the same materials, subjected to air-drying at different RH environments. In order to analyze how porous materials compare to conventional building materials in regards to air RH, the derived isotherms are used as direct input to the building simulation software “BSim” and compared to conventional building materials by performing multiple simulations. The buffering effect of the materials is analyzed by looking at the annual variation of moisture content in the different walls, subjected to the same conditions.




2. Materials

Hemp-lime building materials are composed from the stem of the hemp plant (hemp shiv) and a lime based binder. Depending on the composition of the material, the shiv can represent a large share of the total volume of the material (up to 85% or more). Therefore, it is important to ensure that the shivs are suitable for construction purposes. This is achieved if they are free of seeds, vegetable content, dust and fiber. Shivs used for preparation of material composites in this paper are in the range from 1-9 cm with density of 102 kg/m³ and small amount of fiber. Their moisture content, prior to mixing was determined to be 7.68% by mass, using the desktop tool Mettler Toledo Moisture Analyzer HE73.

The binder formulation used for hemp-lime composites in the majority of cases consist of hydrated (air) and hydraulic lime, pozzolanic additives, sand and cement. The composition of the binder and its proportion to shives in the mixture can be adjusted to produce hemp-lime materials with densities ranging from 200 – 800 kg/m³ [8].

The aim for the developed materials in this paper is to create two materials representing hemp-lime composition in both low and high limit of the density range. Furthermore, it is to compare those materials to a third material, which is commercially available and lies in the middle of the typical density range. Table 1 presents an overview of the tested materials.

Table 1. Overview of tested materials and their properties.

	Low Density (LD) Hemp-Lime	Medium Density (MD) Hemp-Lime	High Density (HD) Hemp-Lime
Specimen image			
Dry Density [kg/m ³]	157 ±2	327 ±3	570 ±7
Composition	Hemp, Air Lime, NHL 3.5, Fly Ash	Commercial binder	Hemp, Air Lime, NHL 3.5, Fly Ash, Sand
Thermal Conductivity [W/(m.K)]	0.07	0.1	0.13
Specific heat capacity [J/(kg.K)]	400	340	400

3. Methods

3.1. Experimental methods

Standard [9] specifies two possible methods, that can be used to determine the hygroscopic sorption properties of building materials. Those are climatic chamber method and desiccator method, using saturated salt solutions. The work presented in this paper follows the desiccator method. Table 2 shows the necessary testing equipment and requirements associated with each element, as well as, conditions obtained during the experiment. As shown in Table 2, all experimental equipment satisfy the requirements set out by the standard.

The procedure for determination vapor sorption isotherms using desiccator method stated in [9] begins with oven dried specimens placed in the weighting cups. The specimens are then placed in the desiccator with lowest RH and the lid of weighting cup is removed. Specimens are weighted continuously in intervals of at least 24 hours until equilibrium is reached.

The standard specifies that equilibrium is achieved when the change in mass of the specimens is less than 0.1% of the total mass of the specimens between three consecutive weightings. The specimens are then moved to the next desiccator with higher RH and the procedure is repeated. When the specimens have reached equilibrium at the highest RH absorption curve is obtained. Then the specimens are moved to RH environments in decreasing order to obtain the desorption curve.

Four salt solutions were prepared in accordance with standard [9]. Table 3 lists the chosen salt solutions, their design and measured RH. The amount of salt and water mixed together are carefully weighted before mixture on a precision scale with accuracy of ±0.01 gram. The correct mixing temperature of the distilled water is ensured with high precision thermometer F200

with accuracy of ± 0.01 °C. Despite those efforts, some differences between design and measured RH are present. This can be a result of partial dissolution of the mixed salt.

Table 2: Elements and requirements of the standard desiccator method.

Element	Standard Requirement	Experiment Condition
Weighting cups and lids	Tight fitting cup and lid that do not absorb water	High quality plastic boxes with lock mechanism.
Balance	Accuracy of $\pm 0.01\%$ of specimen mass (Minimum required accuracy of scale ± 3.5 g)	Denver Instrument DI2200; Weighting accuracy of ± 0.01 g.
Drying oven	Drying in accordance with [10].	Materials dried at 105 °C
Desiccator	Able to maintain relative humidity within maximum variations of $\pm 2\%$	Maximum variations within adapted desiccators $\pm 0.5\%$
Constant temperature chamber	Able to maintain constant temperature with maximum variations of ± 0.5 °C	Temperature variations within the chamber ± 0.05 °C
Number of test specimens	Minimum 3	4 specimens per material.
Specimen size	Materials with density < 300 kg/m ³ , minimum surface area of 100cm ² .	Active surface area of all specimens 825 cm ²

Table 3: Specifications of developed salt solutions.

	Potassium Acetate	Sodium Iodide	Sodium Bromide	Potassium Chloride
Chemical Formula	KC ₂ H ₃ O ₂	NaI	NaBr	KCL
Mixing temperature of water [°C]	20	25	50	20
Solubility [gr. Salt/ml. of water]	2.53	1.84	1.16	0.34
Design Relative Humidity [%] at 23°C	22.15	28.17	57.57	84.65
Measured Relative Humidity [%] at 23°C	19	34	54	81

Figure 1 shows the experimental set-up used for the experiments. In order to allow for simultaneous testing of four specimens at a time, desiccators are made from plastic bins with airtight lids. Each of the four desiccators is equipped with two small circulation fans, as indicated in Figure 1. This is done to ensure full mixing of the air and create forced convection, which gradually reduces the equilibration time. The circulation fans give off a small amount of heat to the desiccator. To remove that extra heat accumulation and to keep a constant temperature of 23 °C in the desiccator, the temperature of the chamber is set to 20 °C.

To ensure that the results obtained by such experimental set-up are reliable, a comparison is made with air-dried specimens. Each of the three materials is placed in rooms with different RH. The specimens used for this experiment are smaller 100 cm³ rings that were prepared using the same procedure and proportions, as those used in the desiccators.

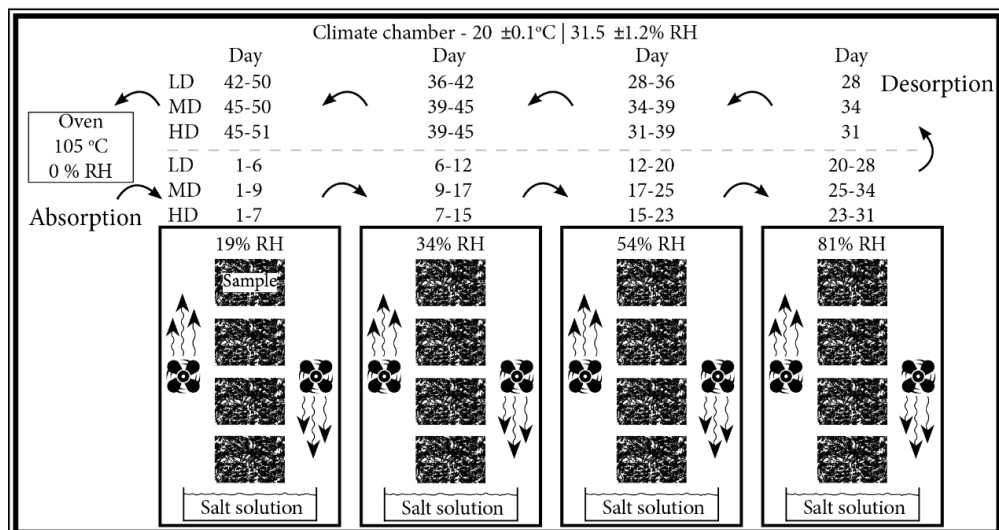


Figure 1: Experimental set up of the standard desiccator method using saturated salt solutions. Duration of equilibration time at each relative humidity environment indicated for each material for absorption and desorption.

Moisture content of the air-dried specimens is calculated based on their dry weight, which is determined by drying the specimens at 105 °C until equilibrium is established. Equilibrium at each environment is determined using the same criteria set out in standard [9]. This method is used for comparison purposes - therefore, only values at desorption are given.

3.2. Simulation methods

The purpose of the performed simulations is to evaluate if materials with different vapor sorption isotherms have direct effect on indoor air RH. Furthermore water accumulation and variation throughout a year are compared for all tested hemp materials and three common building materials.

The calculation software tool BSim is used for performing all simulations presented in this paper. BSim is capable of predicting indoor environmental parameters, power demand and energy consumption of buildings by solving transient, coupled heat and moisture mathematical models. A simulation is made on an hourly basis using Danish Design Reference Year (DRY 2013). The simulation model used for the comparison is a well-defined passive single-family house described in detail by [11].

In order to keep energy requirements of the building constant for all simulation cases, the variation of different materials is performed for all internal walls, where the thickness of the walls is constrained to 96 mm for all cases. Figure 2 shows the different conventional materials used as comparison to the three tested hemp-lime building materials. Moisture transfer in BSim is calculated based on input values of absorption-desorption isotherms and vapor permeability. Vapor sorption isotherms for the simulated conventional building materials are obtained from the software database, where comparison to [12] proved that they are reliable. Hysteresis in the moisture model is accounted for by tracking the history of moisture in a material and its adsorption and desorption isotherm. Depending on the moisture development with time, scanning curves are moving asymptotically towards pure adsorption or desorption.

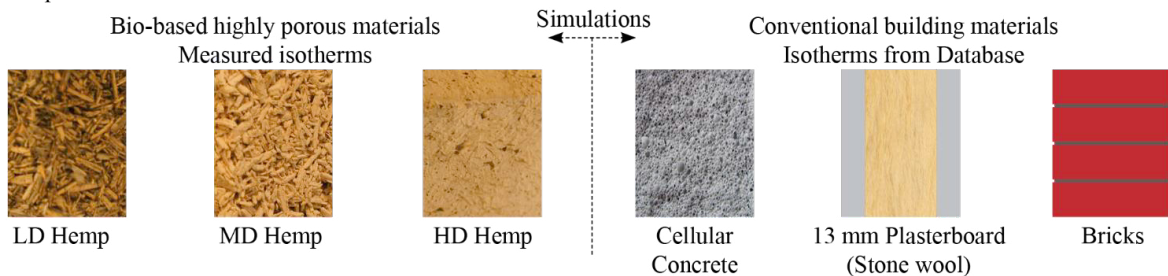


Figure 2: Variated internal wall materials in simulation models. Left: three hemp-lime materials with experimentally derived isotherms, Right conventional building materials with isotherms obtained from BSim software database.

As vapor permeability is not of focus in this work, for hemp-lime materials it is adopted from [4]. Initially choosing vapor permeability according to density was considered, expecting that permeability would decrease for increasing material densities. On the contrary, comparison of work presented by [4] and [13] showed lower vapor permeability for lower density materials ($1.7\text{--}6.2 \times 10^{-11} \text{ kg/(m.s.Pa)}$ for 430 kg/m^3 [4], and $4.14 \times 10^{-10} \text{ kg/(m.s.Pa)}$ for 627 kg/m^3 [13]). Therefore, to observe the effect of variation of isotherms on the indoor environment the choice fell on simulating all hemp-lime materials with the same vapor permeability ($1.7\text{--}6.2 \times 10^{-11} \text{ kg/(m.s.Pa)}$ for RH range from 10 - 82%, respectively). Vapor permeability values for conventional materials are obtained from the software database.

4. Results

4.1. Experimental Results

Figure 3 presents vapor sorption isotherms for the three investigated materials. Isotherm' absorption and desorption lines are drawn as the average moisture content at equilibrium at each of the four RH environments. The bars on the isotherm represent the standard deviation of moisture content obtained by the four different test specimens for each material. As is observed in Figure 3, the HD hemp-lime specimens have the highest standard deviation at each RH environment. This is a result of the higher deviation in density for the tested specimens (see Table 1).

It is also clearly noticed that the lower density hemp-lime materials are capable of absorbing and storing more moisture per unit dry weight than materials of higher density. This can be associated with the higher porosity of the material, where the higher amount of pores in the material matrix provides more surface area. It is also noted that the slope of the absorption curve within the region of 20-55% RH is steeper for low-density materials. This shows that it takes longer time for the surfaces of the lower density materials to be covered by one layer of vapor molecules.

The storage capability of the materials can be associated with the equilibrium moisture content established at the same RH trough absorption and desorption curves. It is apparent that hysteresis loop is present for all three tested materials. Comparing the amount of hysteresis, shows that the amount of moisture content locked inside the materials can also be related to the density. The

average difference in moisture fixation between absorption and desorption is 3.4, 2.3, and 1.3 % by mass for LD, MD, and HD hemp-lime materials respectively.

When comparing the results from the saturated salt solution method (SSM) to moisture fixation by air-drying method (ADM), one can see that the results are in good agreement with each other, as nearly all points fall within the hysteresis loop. Higher values for LD and HD materials in the region above 50% RH can be attributed to the initial state of those air-dried specimens (wet-after mixing). This is believed to be due to a slower desorption rate at higher RH. Despite the fact that the specimens had reached equilibrium in regards to mass change over 24 hours, not all water that could leave the material is desorbed. Such observation was also made by [14].

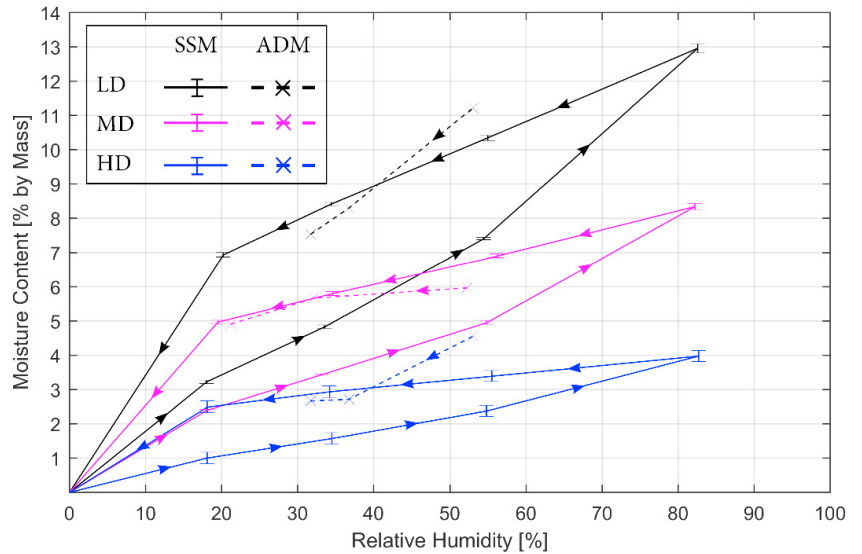


Figure 3: Vapour sorption isotherms for Low (LD), Medium (MD) and High Density (HD) hemp-lime building materials, derived by salt solution method (SSM) and compared to air-drying method (ADM). Up and down arrows indicate absorption and desorption, respectively.

4.2. Simulation Results

Figure 4 shows the variations of moisture content from the average annual moisture content inside the investigated wall. The figure shows that the highest variations are observed for the three hemp-lime materials and cellular concrete. This suggests that those materials buffer more moisture than brick and plasterboard, which is in agreement with what is expected considering that brick and gypsum are classified as moderate in terms of moisture buffering value [1] while cellular concrete and hemp-lime are classified as good and/or excellent. Furthermore, the smaller variation observed in the cases of plasterboard and brick can be directly related to the isotherms used for the simulation. Figure 5 B illustrates a comparison of the isotherms of all simulated materials, where it is clear that plasterboard and brick have much smaller moisture absorption capabilities and no storing capabilities as the neither of the materials observes hysteresis.

Figure 5 A shows a histogram with distribution of air RH within a zone with daily moisture loads. Arrows in the figure mark category ranges, satisfying indoor air RH design criteria in occupied spaces according to [15]. All investigated materials show very similar results in terms of RH in the studied zone and range. In general, all three hemp-lime material give nearly the same results in all RH ranges, with very small differences in the high RH range. This is a result of using the same vapor permeability for all three materials. When comparing hemp-lime to conventional materials, it can be concluded that such bio-based materials can be suitable alternative as they have high percentage of hours in the desired RH regions (40-50% RH); while those in the unwanted region (<30; >60% RH) are low.

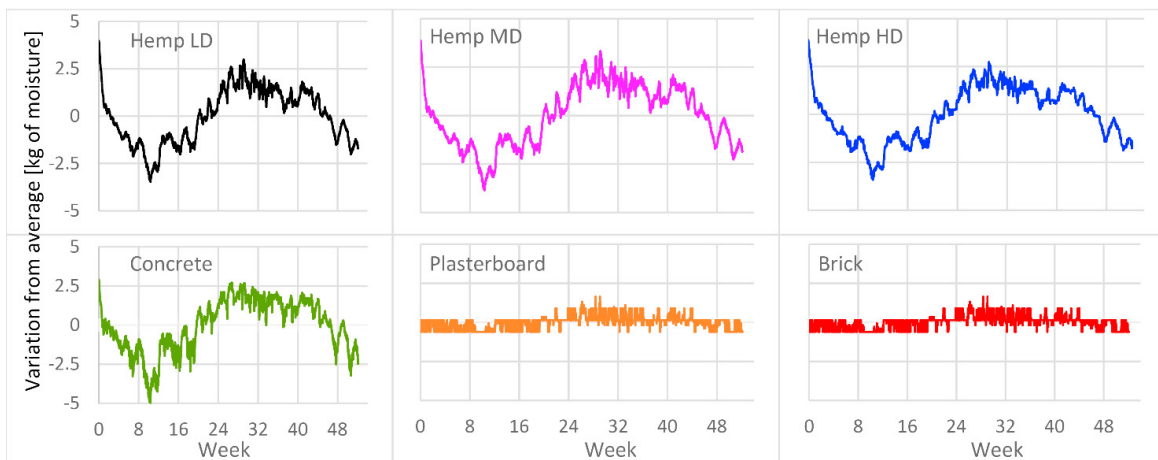


Figure 4 Variations of moisture content from average in internal walls made from different materials, subjected to the same conditions.

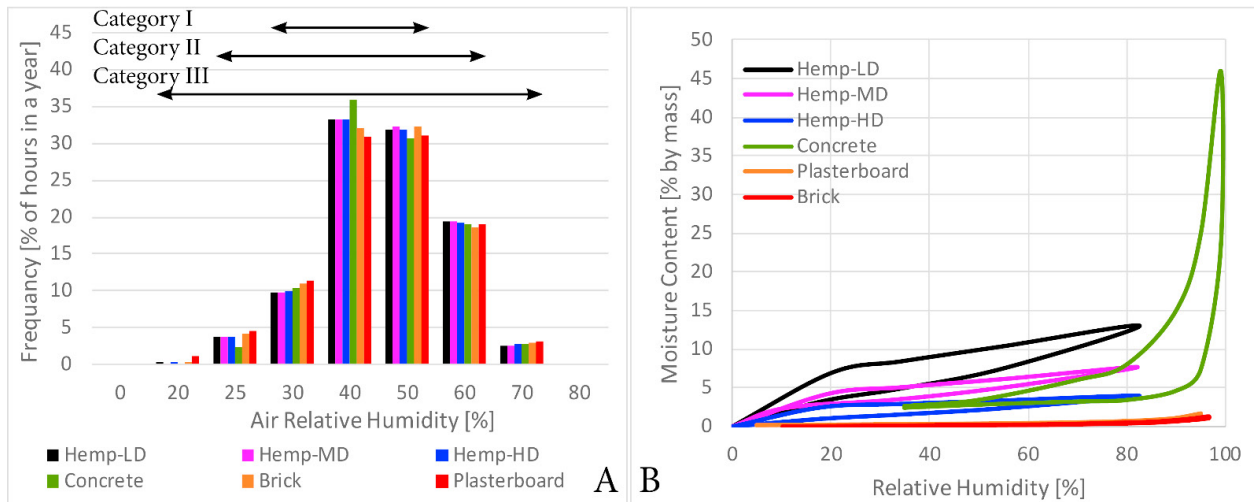


Figure 5 A - Histograms of air relative humidity in zone 1, for bio-based, porous and conventional building materials. Indication arrows for Category requirements set out by [15]; B – Experimentally derived isotherms of hemp-lime building materials compared to isotherms of conventional building materials.

5. Conclusion

This paper investigates the moisture fixation in highly porous hemp-lime building materials. Vapor sorption isotherms are derived using a standard method by saturated salt solutions and compared to results from air-drying method. Results from the two methods are in good agreement with each other. This argumentation is made as all moisture fixation points obtained by air-drying in low relative humidity ranges fall within the hysteresis loop. Discrepancies for low and high density hemp-lime materials between the methods are attributed to slower moisture desorption at high relative humidity.

The observed moisture variations in internal walls are higher for materials with high moisture content per unit weight and hysteresis. Despite the great differences in vapor sorption isotherms and moisture variation in internal walls the air relative humidity distributions in the studied zone shows nearly the same values for all materials. Using a constant vapor permeability for the simulated hemp-lime materials resulted in the same values of air relative humidity in all cases where hemp-lime materials are used as internal walls. In order to obtain results that are more reliable, determination of the vapor permeability is required for each individual material.

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